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AUDIBILITY LIMITS FOR AMPLITUDE AND FREQUENCY MODULATION OF A TONE

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Introduction

The ability of the human ear to perceive slight differences in loudness was investigated in detail for the first time by Riess [3]. He generated a loudness fluctuation by beating two closely adjacent tones, and established that it was audible if the amplitude varied by more than a few percent. /125*

Shower and Biddulph [5] studied the perceptability of slight variations in pitch. They listened to two adjacent, alternating tones and found that a pitch difference of a few parts per thousand was detected.

Helmholtz found that timbre is independent of the phase relation of the component tones. This information is not true without limit, because if one generates a sound from a strong /126 tone and two weaker ones which are very closely adjacent above and below the strong tone, then, as is well known, one observes a variation in loudness or in pitch, depending on the phase relation. In this case one can distinguish the phase relations of the component tones quite well. Apparently the closeness of the component tones enables the ear to follow the time course of the fluctuation. In this way the ear gets a criterion for phase.

* Numbers in the margin indicate pagination in the original foreign text.

We wish to investigate where the boundary between phase sensitivity and phase insensitivity is for all pitches and loudnesses. For this we used sinusoidally amplitude-modulated sound vibrations and sinusoidally frequency-modulated sound vibrations, and compared the audibility of both types of modulation with the same amplitude spectrum.

1. Occurrence of the Modulations

When we speak of tones which are frequency-modulated or amplitude-modulated, we think primarily of the modulation which we hear in musical presentations, the so-called vibrato. This vibrato can be frequency or amplitude modulation. Almost always the frequency and amplitude are independent, so that both types of modulation occur simultaneously in practical cases. We shall not have any further concern for the vibrato, but mention that this modulation is always considered plesent, if we use it within certain limits.

In contrast, frequency or amplitude modulation can be unpleasant if they appear throughout an entire selection of recorded music, and are due to the technical inadequacy of the reproduction or the recording. As periodic modulations, the eccentrically running disc record and the "thump" of the tape recorder drive shaft are examples for low modulation frequencies [1]. With sound film, a periodic frequency modulation occurs if the jerky film feed is not completely compensated for at the point of sound takeoff [2]. With a loudspeaker, there is frequency modulation due to the "Doppler effect" if a low tone (large excursion) and a higher tone (smaller excursion) are reproduced simultaneously by one diaphragm. Then the frequency of the high tone changes periodically with the frequency of the low tone. Statistical amplitude and frequency modulation occur at high modulation frequency with the tape recorder if the tape develops transverse and longitudinal vibrations ahead of the reproducing head.

Another disturbing modulation which occurs often is that from a nonlinear characteristic if it is fed simultaneously with two tones which are widely separated.

The wobble tone is used in special cases as a desired frequency modulation. For acoustical physiological studies, it is practical to use only pure amplitude or frequency modulations because it is simple to represent them mathematically. The measurements with these pure modulations provide the results which we use as the basis for a discussion of all the occurrences of modulation.

Before going on to describing such measurements and their results, we must summarize the symbols used in the formulas, / 127 introduce the relations between amplitude modulation (AM) and frequency modulation (FM), and define the individual values.

2. The Mathematical Representation of the Modulation Types

We shall limit ourselves here to a sinusoidal change in the oscillations and compare the two types of modulation with each other. As a very slight modulation is sufficient for acoustic effect with FM, we will consider the case of weak sinusoidal modulation particularly for FM. We arrive at the following comparison with the corresponding definitions.

AM

Time formula: $F(t) = (A + a \sin \omega t) \sin (\Omega t + \varphi_0)$

Divided into individual oscillations:

$$F(t) = A \sin (\Omega t + \varphi_0) + \frac{a}{2} \cos [(\Omega - \omega) t + \varphi_0] - \frac{a}{2} \cos [(\Omega + \omega) t + \varphi_0]$$

a = amplitude variation

$f_0 = \Omega / 2\pi$ = carrier frequency

$f_{mod} = \omega / 2\pi$ = modulation frequency

$f_0 + f_{mod}$ = upper side frequency

$m = a/A$ = AM degree

$f_0 - f_{mod}$ = lower side frequency

FM

$$F(t) = A \sin \left(\Omega t + \frac{\Delta\Omega}{\omega} \sin \omega t + \varphi_0\right)$$

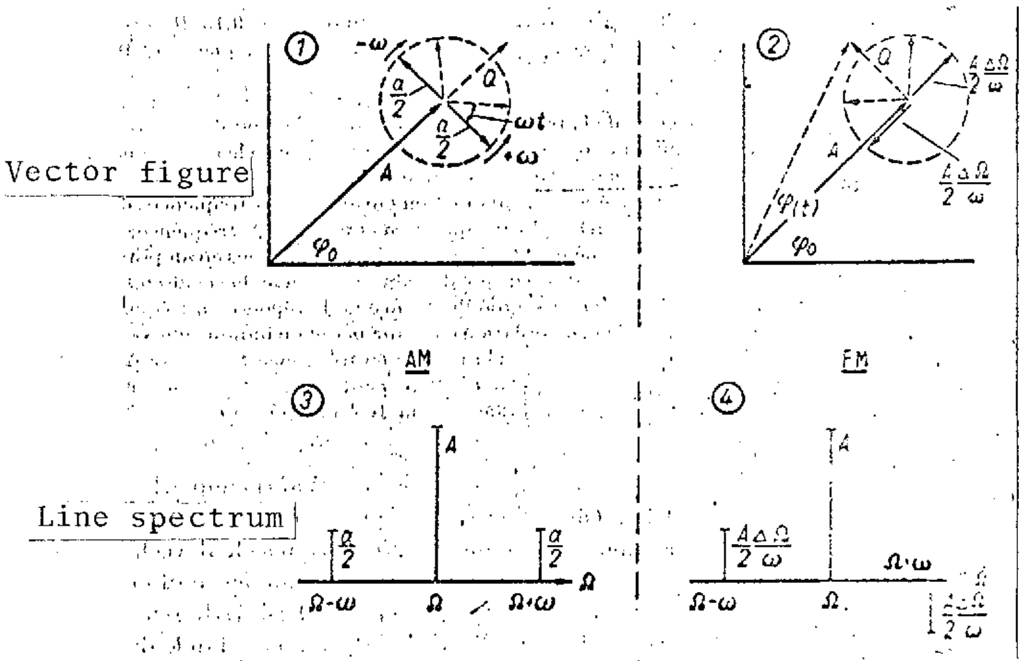
Approximation for $\Delta\Omega/\omega < 1$:

$$F(t) = A \sin (\Omega t + \varphi_0) - \frac{A}{2} \frac{\Delta\Omega}{\omega} \sin [(\Omega - \omega) t + \varphi_0] + \frac{A}{2} \frac{\Delta\Omega}{\omega} \sin [(\Omega + \omega) t + \varphi_0]$$

$\Delta f = \Delta\Omega / 2\pi$ = frequency variation

$\Delta f / f_0 = \Delta\Omega / \Omega$ = FM degree

$\Delta f / f_{mod} = \Delta\Omega / \omega$ = modulation index



Figures 1 - 4. Vector figures and line spectra for amplitude modulation and frequency modulation at low modulation index.

The modulation index is not very easily understood and says nothing of the frequency variation. But, with the equivalent phase modulation, it corresponds to the equivalent phase deviation $\hat{\varphi}$. As sinusoidal frequency and phase modulation cannot be differentiated from each other, the phase deviation, which gives an indication of the variation in phase is also a suitable representation for this quantity.

As the vector figures and the line spectra show (Figures 1 - 4), AM and FM at low modulation index differ only in the rotation of the varying vector Q. With AM, Q is in phase with the carrier, A, while with FM Q is rotated by 90° in relation to A. Except for the phase rotation, the vector figures and line spectra are identical if Ω and ω are the same, and if the ratio a/2:A for AM corresponds with the ratio $\Delta\Omega/2\omega:A$ for FM; that is, if the degree of modulation, a/A, is equal to the modulation index, $\Delta\Omega/\omega$.

For FM, the approximation is accurate within 5% up to $\Delta\Omega/\omega = 0{,}25$; for $\Delta\Omega/\omega > 0{,}5$ the error is greater than 20%, so that the approximation is no longer justified. Then new lines appear, while the maximum degree of modulation for AM is attained at a/A = 1.

3. The Measuring Place and Measuring Method

a) Tone frequency generator capable of frequency and amplitude modulation

For the acoustic studies, a generator was built on the heterodyne oscillator principle according to the block diagram of Figure 5. The AM and the FM are expressed in the voltage provided from Generator 1, the AM through anode voltage modulation of the screen-grid-current-limited LC Generator 1 and the FM through a reactance tube connected in parallel to the resonant circuit of Generator 1. The relatively low voltage from Generator 1 is modulated by the large voltage from Generator 2, with suppression of the latter at two diodes. The modulation product is amplified with very low noise and matched to the following low-pass filter with a delay time equalizer. An output stage with negative feedback yields the desired internal resistance and the desired low-noise output voltage.

Frequency range: 30 Hz - 18 kHz with logarithmic scale;
Voltage output: frequency-independent up to 12 V_{eff} into 600 Ω at $k < 0.5\%$; / 128

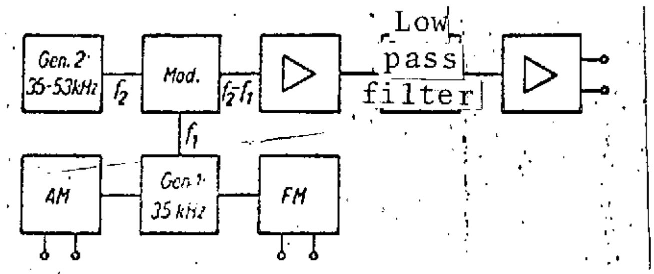


Figure 5. Block diagram of the tone frequency generator capable of frequency and amplitude modulation.

Degree of modulation: independent of the carrier frequency
($m < 80\%$; $1\ \text{Hz} < f_{mod} < 6\ \text{kHz}$);

Frequency variation: independent of the carrier frequency
($\Delta f < 250\ \text{Hz}$; $1\ \text{Hz} < f_{mod} < 6\ \text{kHz}$).

b) The Measuring Method

In the measurements we attempted to keep the error, which is relatively large for all subjective measurements, within narrow limits by the yes-no method. With the yes-no method the observer need not say whether he hears much or little. He need only state whether he hears anything at all or not, or if he perceives a difference or not.

Thus, we determine the limiting curves which separate the regions of different perceptions from each other. By establishing the measurement of such limiting curves, we obtain these accurately enough that we can make reliable quantitative statements. Through suitable choice of the experimental conditions it is even possible often to obtain a measurement in a different way. Thus, for instance, we can hold the loudness constant and change the degree of modulation; or we can hold the degree of modulation constant and change the loudness, in both cases noting the occurrence of audibility of the modulation.

In the measurement itself the observer is first offered a modulation which he can hear well. With alternations at intervals of about 3 seconds, he is then presented the modulated and the unmodulated tone. The degree of modulation or the loudness are reduced until the observer can no longer detect a difference. Then the degree of modulation or the loudness are increased until the observer can again notice the difference. The average value between "not hearing" and "hearing again" is taken as the measurement. The measurements from four observers are averaged and plotted as a point.

Unless otherwise stated, the electroacoustic transducer was an electrodynamic earphone which is equalized from 30 Hz to 15 kHz to ± 3 dB, and which has a very low noise factor [6].

4. The Limiting Amplitude Modulations

a) The dependence on the modulation frequency

Figure 6 shows the just-audible degree of modulation plotted versus the modulation frequency at a constant carrier frequency of 1000 Hz. The results presented were measured by, and are averages from, four observers. Borrowing from the concept of limiting noise factors, we wish to call these modulations the limiting modulations. These limiting modulations depend on the loudness, so that the loudness is a parameter for the family of curves.

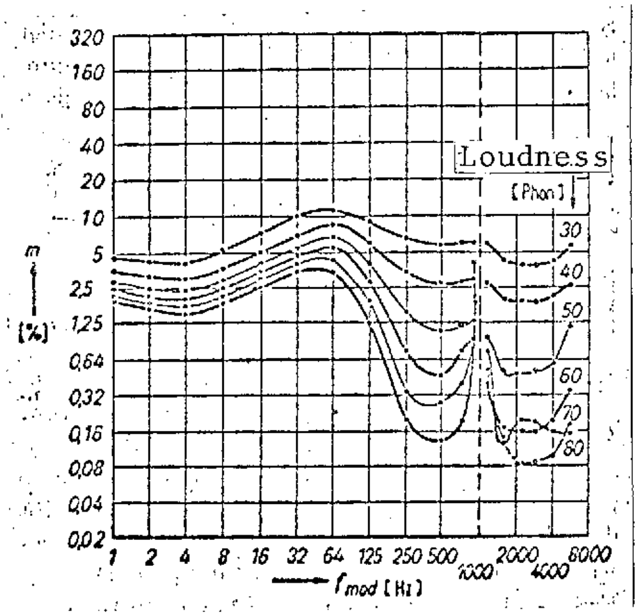


Figure 6. Limiting amplitude modulations (f_o = 1,000 Hz).

We shall discuss the lowest curve, which is the limiting modulation for 80 phon, first. At this rather great loudness we can, at low modulation frequencies, perceive a loudness variation even at a degree of modulation of only 2%. The relative difference between the maximum and the minimum loudness was 4%, corresponding to 0.35 db. At a frequency of 1000 Hz and a loudness of 80 phon we can still perceive a loudness difference of 0.35 db. These two loudnesses were not presented in immediate succession, but with a sinusoidal transition. With sudden change of the loudness, still smaller differences are just perceptible [3]. If we continue to follow our curve, we find a minimum at some 4 Hz. This corresponds to a maximum sensitivity of the ear at a variation rate of 4 Hz. The curve rises again at higher modulation frequencies, as the sensitivity diminishes. The acoustic impression is that the ear can follow the variation up to about

4 Hz, so that the entire change in loudness is perceived. At f_{mod} the ear hears essentially the maximum loudness. The tone /129
impression proper is lacking between the maxima. It seems as if the time constant of the ear is so large that it can still follow the variation up to 4 Hz. Beyond that, analogous to a rectifier circuit, it can only record excitation during the maxima.

The tone begins to become uneven at about 20 Hz modulation frequency. We can no longer hear a loudness variation, but have the impression of an impure, bubbling tone [4]. The sensitivity has diminished to half at f_{mod} = 50 Hz in comparison to f_{mod} = 4 Hz.

Above 100 Hz the sensitivity increases rapidly again. The upper and lower side frequencies of the modulated 1000 Hz tone begin to become audible. This tone impression remains up to the highest modulation frequencies and is affected only by the masking which becomes particularly apparent at a modulation frequency of 1000 Hz. Here the lower side frequency drops toward 0, while the upper side frequency is at 2000 Hz and is strongly masked by the carrier frequency, f_o = 1000 Hz.

At modulation frequencies above 1000 Hz the side frequencies originate so that only positive frequencies occur. They determine the limiting modulation corresponding to their frequency position and the masking. Thus, we can differentiate three principal characteristic regions which, of course, partially merge into each other:

f_{mod}	
1 . . . . . 20 Hz	audible variation of the loudness
20 . . . . . 100 Hz	unevenness of the tone
> 100 Hz	audibility of the side frequencies.

b) The dependence on loudness

Now let us consider the other curves for other loudnesses. We find essentially the same course. The observers differentiate the three principal regions at all loudnesses. The acoustic impression of the perturbation at the limiting modulation is similar for various loudnesses. The minimum at 4 Hz appears on all curves. The separation of the curves is greater for loudnesses below 50 phon. The effect of the sound pressure on the limiting modulation is slight at loudnesses above 50 phon, while it becomes more distinct at lower loudnesses.

The curves run parallel up to about 100 Hz. But as soon as the upper and lower side frequencies become audible, the separations increase. At high loudnesses the masking has a strong effect, so that the curves partially run through each other, particularly if the modulation frequency becomes near the carrier frequency.

As soon as the side frequencies become audible, we must assume that the separation of the limiting modulation curves at constant loudness is prescribed by the sound pressure difference and the masking. For instance, let us consider the 40 phon curve and neglect the masking (i. e., we assume that any tone which exceeds the hearing threshold is audible). Let us also replace the hearing threshold by the 0 db line. Then the side tone must become audible if its amplitude is 40 db lower than the amplitude of the carrier frequency; that is, at a degree of modulation of some 2%. This agrees well with the measurement. It can, therefore, be assumed that after the sharp drop of the limiting modulations at f_{mod} = 125 Hz only the sound pressure or the emergence of the side frequencies out of the hearing threshold, and the masking, determine the limiting modulation, so that this can be calculated for the third principal region if we have masking measurements.

5. The Limiting Frequency Modulation

a) As a function of the modulation frequency

The just-audible frequency variation is plotted as a function of the modulation frequency in Figure 7, again at the fixed frequency of 1000 Hz. Here again, the loudness is the parameter. The lowest curve for 80 phon likewise shows a sensitivity maximum at 4 Hz. At that point a frequency variation of 1 Hz is perceived. This means that at 1000 Hz a frequency difference as low as / 130
2 Hz absolute or 2 $^{o}/oo$ relative is audible [5].

The curve for frequency modulation at low modulation frequencies appears to be similar to that for the limiting amplitude modulation.

Even the acoustic impression shows parallels. For instance, the ear can still follow the variations of the frequency up to some 4 Hz, while at modulation frequencies up to some 20 Hz the frequency variation seems harsher, so that the ear no longer seems quite able to follow the frequency change. The sensitivity decreases again. Above 20 Hz the tone becomes uneven and bubbling, until the side frequencies become audible at about 125 Hz. Here, too, these are affected only by the masking and are perceived up to the highest modulation frequencies.

b) As a function of the loudness

The slight dependence of the limiting modulation frequency at 50 . . . 80 phon and low modulation frequencies is striking. Here the measurements of different observers often overlap. For clarity, and because a detailed subsequent test shows that the just-audible frequency variation in the region studied always increases with decreasing loudness, although perhaps very slowly, the limiting curves are plotted in superimposition. But even

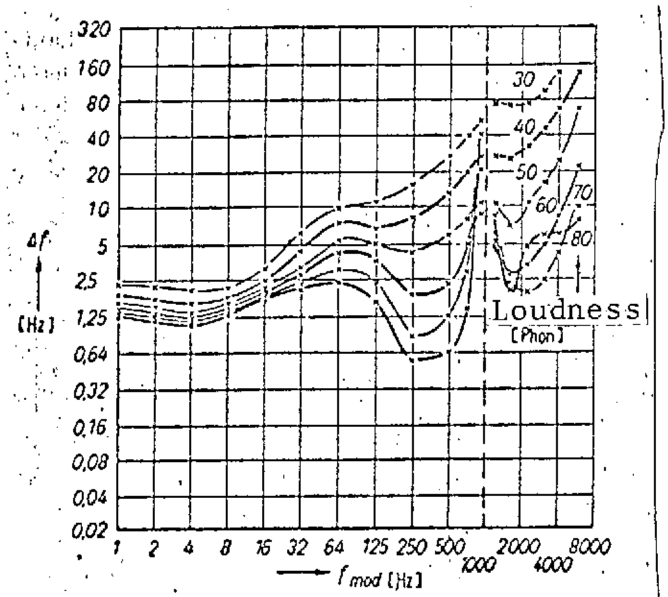


Figure 7. Limiting frequency modulations (f_o = 1000 Hz).

here the separation is distinctly greater below 50 phon, so that the sensitivity drops off considerably faster at low loudness than at moderate and high loudness, where it remains almost constant. At low modulation frequencies, the loudness parameter produces essentially a parallel shift, while at f_{mod} = 40 Hz the curves diverge more and more, so that they are determined only by the distance of the carrier level from the hearing threshold and by the masking.

6. The Relation Between the Limiting Amplitude and Frequency Modulations

If we wish to compare the amplitude and frequency modulations at the same line spectrum, we must select as the ordinate the modulation index (FM), the phase variation (PhM) or the degree of modulation (AM), already described in Section 2.

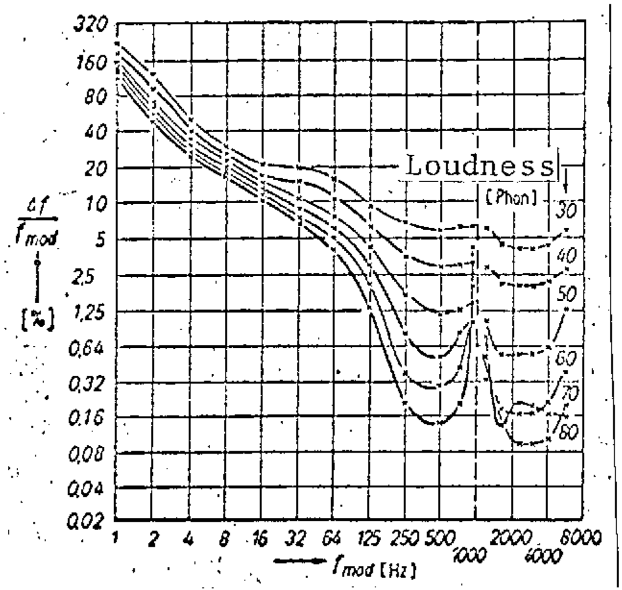


Figure 8. Limiting frequency modulations (f_o = 1000 Hz).

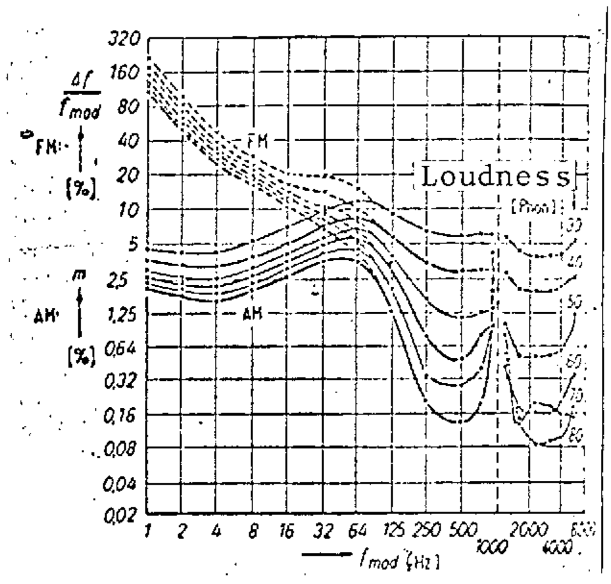


Figure 9. Limiting amplitude and frequency modulations (f_o = 1000 Hz).

This has already been so chosen for amplitude modulation. For frequency modulation this presentation is shown in Figure 8, where the just-audible modulation index (at f_o = 1000 Hz) is plotted versus the modulation frequency. The horizontal lines in Figure 7 would correspond to 45° lines from upper left to lower right in Figure 8.

If we plot Figure 8 in Figure 6, we get Figure 9. In this we see clearly how the limiting amplitude modulation and frequency modulation merge into each other at f_{mod} = 80 Hz. There we here the side frequencies, and apparently the phase relation between the varying portion, Q, of the two modulation vectors and the carrier play no part. The situation is different for the lower modulation frequencies, where the two families of curves distinctly diverge [7]. To be sure, we must still consider our approximation in Section 2. If we allow an error of 5%, the validity of our approximation is limited at m = 20%. Up to there the difference between AM and FM also exists in the phase relation of vector Q to the carrier.

We must establish, therefore, that / 131

1. the ear is more sensitive to amplitude modulation than to frequency modulation at low modulation frequencies;
2. at a carrier frequency of 1000 Hz a difference in the phase relation is audible below a modulation frequency of some 80 Hz, and the ear can no longer distinguish between amplitude modulation and frequency modulation above 80 Hz;
3. the frequency at which the difference in the phase relation can no longer be perceived (limiting phase frequency) does not depend on the loudness.

7. The Limiting Amplitude Modulation and the Limiting Frequency Modulation as Functions of the Carrier Frequency

The considerations up to this point apply only for the constant carrier frequency of 1000 Hz. According to the determinations in the preceding section, the question of how the double diagram of Figure 9 looks at other carrier frequencies is an obvious one.

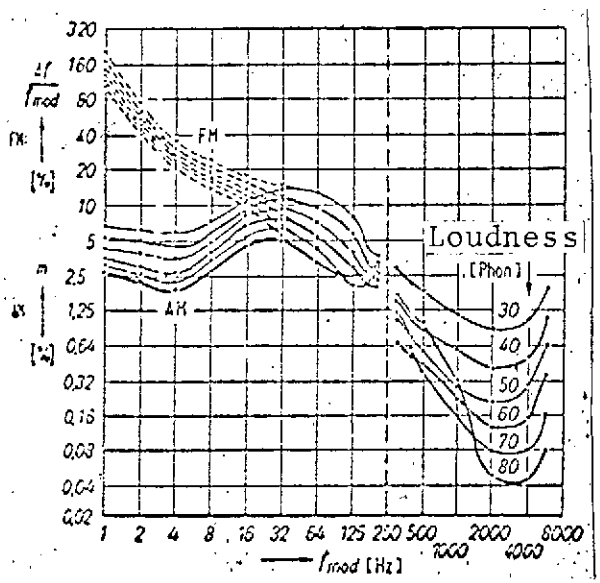


Figure 10. Limiting amplitude modulations and limiting frequency modulations (f_o = 250 Hz).

We shall answer this question now, but wish to recall that some 1,000 individual measurements are needed to set up the double diagram in Figure 9. We must make the same expenditure for every other carrier frequency.

The measurements were done for carrier frequencies of 65 Hz, 125 Hz, 250 Hz, 500 Hz, 2000 Hz, 4000 Hz and 8000 Hz, in the same manner [8]. The double diagrams for f_o = 250 Hz and f_o = 4000 Hz

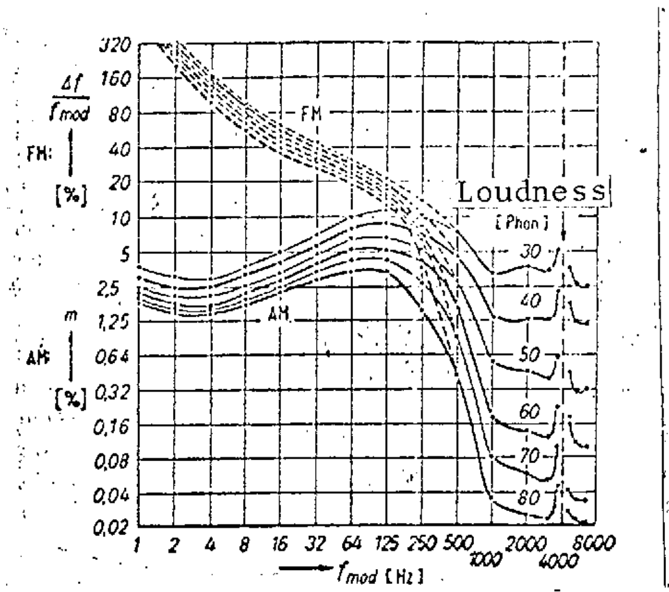


Figure 11. Limiting amplitude modulations and limiting frequency modulations (f_o = 4000 Hz).

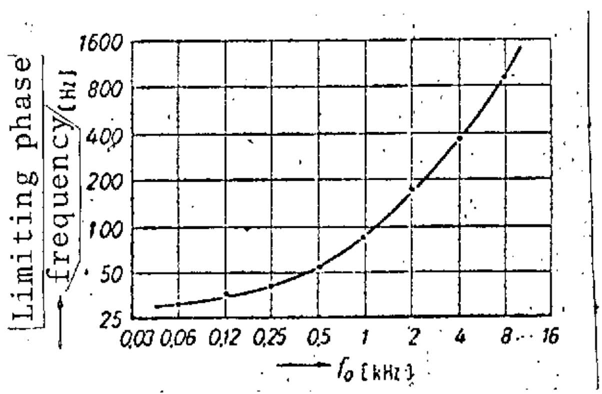


Figure 12. The limiting phase frequency as a function of the carrier frequency.

are shown in Figures 10 and 11. The course of the curves is similar in both cases. The minimum at 4 Hz modulation frequency, the confluence of the two families of curves, and the large separation of the individual curves at large modulation frequencies remain characteristic. But the difference in the frequencies at which the families of curves come together, the different phase limiting frequency, at f_o = 250 Hz and f_o = 4000 H_z, is striking. In contrast, the limiting phase frequency is also independent of the loudness here.

Now if we plot the limiting phase frequency as a function of the carrier frequency, it rises with rising carrier frequency. Figure 12 shows this curve, which separates the upper region in which the phase relation is not audible from the lower region in which the ear can differentiate a difference between the phase relations of two side bands and the carrier. It is not quite correct, therefore, to say that the ear does not hear any phase difference. We must, then, give good attention to our /132
electroacoustical transmission paths so that the modulation is correctly reproduced in the lower range.

8. The Effect of the Frequency Response of the Transmission Path on the Limiting Frequency Modulation

In Figures 9, 10 and 11 we have seen that the ear is much more sensitive to amplitude modulation than to frequency modulation at low modulation frequencies and the same line spectrum. This fact must be considered in transmission systems. In almost all transmission paths a large part of the slow frequency modulation is converted into amplitude modulation.

Consider now a loudspeaker set up in a normal room. If the frequency response of this system is measured with the measuring microphone at some point in the room, the frequency response is

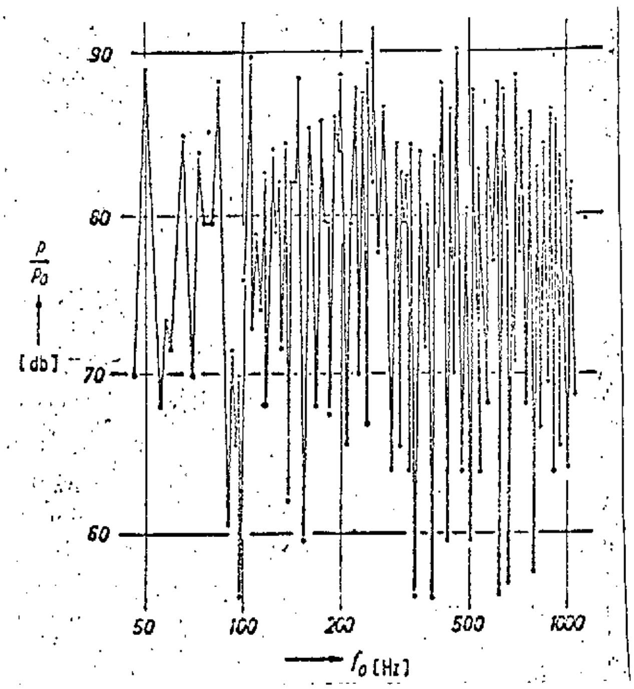


Figure 13. Frequency response of a loudspeaker in a weakly damped space; microphone 2.5 m from the loudspeaker.

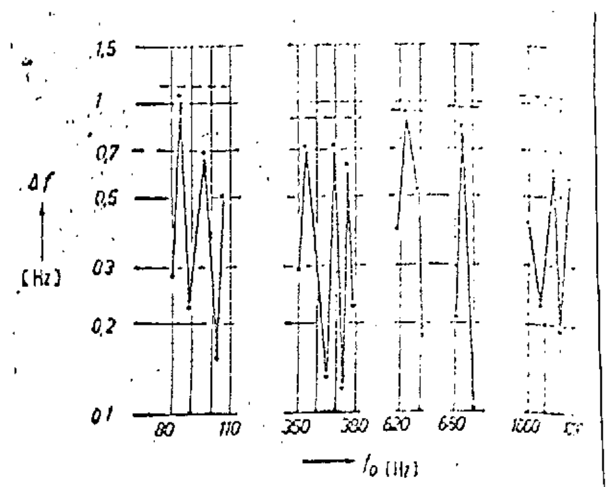


Figure 14. Apparent limiting frequency modulation in a weakly damped space. Observer 2.5 m from the loudspeaker.

not flat, even if the loudspeaker were to be an ideal one. Rather, it has large and steep peaks and valleys. For instance, Figure 13 shows the frequency response of a good loudspeaker in a relatively undamped room, measured at a distance of 2.5 m from the loudspeaker. With such a frequency response, of course, any existing frequency modulation would be converted into strong amplitude modulation, which we could perceive as such, according to its strength. If we increase the frequency modulation slowly from zero, it can very well happen that the resulting amplitude modulation is perceived first, simulating an excessively low limiting frequency modulation.

Thus, Figure 14 shows the subjectively registered limiting frequency modulation at an average loudness of 70 phon, with the observer taking the place of the measuring microphone. Some points have been registered with different carrier frequencies. There appears to be a sudden strong drop below the normal value registered with the headphones with a flat frequency response (dashed line). The deviations increase up to a factor of 10 and always appear if the carrier frequency is at the edge of the transmission frequency response.

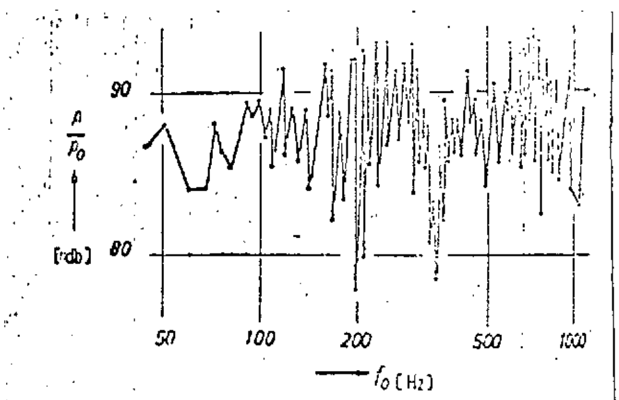


Figure 15. Frequency response of a loudspeaker in a weakly damped space; microphone 25 cm from loudspeaker.

The frequency response shown in Figure 15 was recorded under the same conditions, but at a distance of 25 cm. The effect of room resonances is considerably less, even less than in a normal room at a distance above 1 m. The deviations of the limiting frequency modulation (Figure 16) from the normal value are correspondingly also smaller. They are still at about a factor of 4 because the flanks of the resonances are still steep. /133

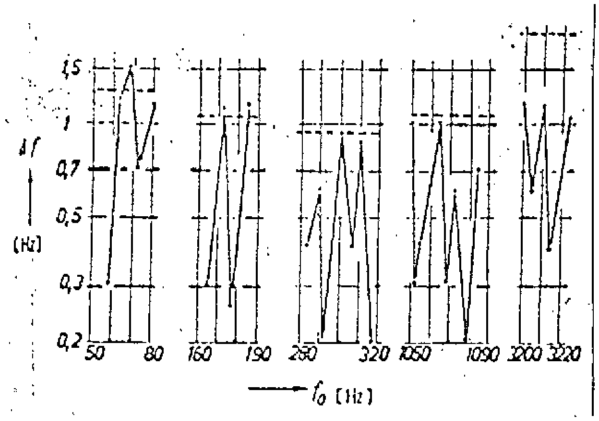


Figure 16. Apparent limiting frequency modulation in a weakly damped space. Observer 25 cm from the loudspeaker.

It is obvious to determine the steepness of the frequency response at which the audibility of the frequency modulation is just retained and at which the audibility of the amplitude modulation which is becoming audible does not go below that of the frequency modulation. This steepness is inversely proportional to the separation of the limiting amplitude modulation from the limiting frequency modulation at 1 Hz modulation frequency. It is shown in absolute quantities in Figure 17. This curve applies for the sensitive low modulation frequencies. Up to 500 Hz the allowable steepness is only 0.17 db/Hz, and it becomes even much smaller at high frequencies. This also explains why the limiting

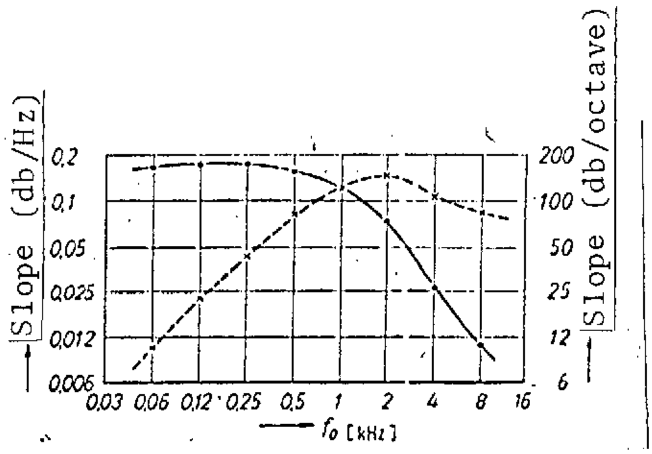


Figure 17. Allowable slope of the transmission path frequency response for true-to-nature transmission, in db/Hz (solid) and db/octave (dashed).

modulation never again reaches the normal value at high carrier frequencies in Figures 14 and 16. There is no longer a place there at which we hear the frequency modulation as limiting modulation. We hear the resulting amplitude modulation there first.

If, therefore, we wish to attain accuracte reproduction of the frequency modulation at low modulation frequencies, the requirements on the transmission path and especially on the electroacoustical transducer are very great. The loudspeaker itself already has gradients in its frequency response (measured in a free sound field) which exceed the allowable value, especially at resonance points. These, however, are far surpassed by the resonances of the reproduction room and the gradients linked with them, in most cases. Therefore it is not practically possible for us to reproduce music, true to the original, in a room with a loudspeaker.

In the reproduction of music with phonograph records or tape recording, we must clearly understand that it is not the frequency modulation originating in the mechanism which directly disturbs the listener. Rather, it is the amplitude modulations, which are only produced for the listener through the room resonances out of the frequency modulation which is in itself inaudible to the listener. The limit of the allowable frequency variations is, therefore, at the present state of reproduction technology, not determined by the just-audible frequency modulation but by the just-audible amplitude modulation [1].

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15. Supplementary Notes Translation of "Die Grenzen der Horbarkeit der Amplitudenmodulation und der Frequenzmodulation Eines Tones". Acustica, Vol. 2, 1952, pp. AB125 - AB133.		

16. Abstract

Measurements have been made of the just-perceptible amplitude modulation and the just-perceptible frequency modulation of pure tones of different pitch and loudness level as a function of the modulating frequency. Below a certain modulating frequency (the so-called phase limiting frequency) the ear is able to distinguish between the two kinds of modulation and perceives the amplitude modulation much better. Above this phase limit frequency there is no perceptible difference between frequency modulation and amplitude modulation. The phase limit frequency has a value of about 30 Hz for low-frequency tones and rises for 1 kHz for tones with a frequency of about 10 kHz. The influence of the frequency response of the transmission system upon the perceptibility of frequency modulation has been investigated and a certain slope of the frequency response is given which converts a just perceptible frequency modulation into a just perceptible amplitude modulation. This permissible slope .

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